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UNPUBLISHED PRELIMINARY DATA

NEUTRINO-SPECTROSCOPY OF THE SOLAR INTERIOR*

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An experiment is currently underway [1] to test directly the theory of [redacted] stellar energy generation by observing the relatively high-energy neutrinos (14 MeV maximum energy) emitted from the interior of the sun in the rare mode of the proton-proton chain that involves B^8 [2]. As a follow-up to this experiment, the author has proposed [3] that a program of neutrino-spectroscopy of the solar interior be carried out to determine quantitatively the conditions in the interior of the sun by using a variety of neutrino-absorbers having, for example, different absorption thresholds. It would be particularly desirable to try to observe the numerous low-energy neutrinos from the basic reaction, $H^1(p,e^+\nu_e)H^1$, of the proton-proton chain (0.43 MeV maximum energy) and from the frequently occurring $Be^7(e^-,\nu)Li^7$ reaction (0.86 MeV maximum energy). The ratio of B^8 neutrinos to low-energy neutrinos would provide a crucial and stringent test of current theories of the interior of main sequence stars. If no neutrinos are detected in the Davis-Harmer experiment [1] (0.81 MeV threshold energy), it will be even more desirable to try to observe the low-energy neutrinos.

In this note we present some theoretical results concerning the following neutrino absorbers: H^3, Li^7, B^{11}, and Rb^{87}. Two of these absorbers (H^3 and Rb^{87}) can detect primarily the low-energy solar neutrinos [4] and the other two [5] (Li^7 and B^{11}) are primarily sensitive to the B^8 neutrinos. In addition, Li^7 and B^{11} can be used to establish the direction of the neutrino source

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(presumably toward the sun) by observing the direction in which the created electrons are produced [6]. The ability of targets made from Li^7 or B^{11} to distinguish the direction of the neutrino source is especially valuable since it will probably be difficult to demonstrate by the method of Davis and Harmer that neutrinos observed in their experiment come from the sun rather than a galactic background [1].

The cross sections for absorption of neutrinos from the most important sources in the sun are given in columns two through six of table 1 for each of the four targets mentioned above. These cross sections include [7] corrections due to excited-state transitions and have been averaged over the appropriate incident neutrino spectra. In column seven of table 1, the asymmetry parameter α is given for each of the isotopes listed [8]. The parameter α determines the extent to which the outgoing electron indicates the incident neutrino direction in a reaction such as:

$$\nu + Li^7 \rightarrow e^- + Be^7 . \tag{1}$$

The angular distribution for a reaction such as (1) is of the form:

$$\frac{d\sigma}{d\Omega_e} = \frac{\sigma_{total}}{4\pi}\left[1 + \alpha\,\frac{\underset{\sim}{v}_e}{c}\cdot\hat{q}\right], \tag{2}$$

where $\underset{\sim}{v}_e$ is the outgoing electron's velocity and $\hat{q}$ is a unit vector in the direction of the incident neutrino's momentum. For the V-A theory [6],

$$\alpha = \frac{\langle 1\rangle^2 - \frac{1}{3}\,C_A^2\,\langle\sigma\rangle^2}{\langle 1\rangle^2 + C_A^2\,\langle\sigma\rangle^2}, \tag{3}$$

where $\langle 1\rangle$, $\langle\sigma\rangle$ are reduced matrix elements with the usual meaning [9].

In order to convert the cross sections given in table 1 into expected numbers of reactions per second per target particle, one must multiply by the predicted solar neutrino fluxes. Table 2 gives the predicted numbers of neutrino-induced reactions per second per target particle from the most important solar-neutrino sources; the fluxes are taken from the work of Sears[10] and the uncertainties shown represent the present author's estimates [7] of uncertainties in the flux predictions.

An experiment that uses either Li^7 or B^{11} as a target to detect neutrinos from B^8 decay and to establish the direction of the neutrino source appears feasible with current technology [5,11]. Experiments designed to detect the low-energy neutrinos are more difficult. For example, ten kilograms of tritium are required in order to obtain a counting rate of 300 events per year induced by solar neutrinos. In addition, the rare events induced by solar neutrinos (which primarily produce electrons with energies of the order of a few hundred keV) must be distinguished from the much more numerous events arising from the normal radioactive decay of tritium (maximum energy of electrons $\sim$ 18 keV), presumably by counting only electrons with energies in excess of 18 keV [12].

Table 1

Cross Sections and Asymmetry Parameters. The subscripts such as p-p or Be^7 indicate the neutrino source in the sun (references two and seven). The cross sections for Rb^{87} refer to the low-lying metastable state of Sr^{87} (reference four).

Target	$\sigma_{p\text{-}p}(\times 10^{+45} cm^2)$	$\sigma_{Be^7}(\times 10^{+45} cm^2)$	$\sigma_{B^8}(\times 10^{+45} cm^2)$	$\sigma_{N^{13}}(\times 10^{+45} cm^2)$	$\sigma_{O^{15}}(\times 10^{+45} cm^2)$	α
H^3	$4.8 \times 10^{+1}$	$1.7 \times 10^{+2}$	$6.7 \times 10^{+3}$	$1.5 \times 10^{+2}$	$2.3 \times 10^{+2}$	- 0.1
Li^7	0	0	$4.5 \times 10^{+3}$	5	$2.3 \times 10^{+1}$	- 0.1
B^{11}	0	0	$1.9 \times 10^{+3}$	0	0	+0.35 ± 0.05
Rb^{87}	7.1	$2.5 \times 10^{+1}$	$9.7 \times 10^{+2}$	$2.2 \times 10^{+1}$	$3.5 \times 10^{+1}$	- 0.3

Table 2

Predicted Number of Neutrino-Induced Reactions per Target Particle per Second.

The fluxes, φ, used here are adapted from the work of R. L. Sears (ref. 10).

Target	$(\varphi\sigma)_{p\text{-}p} \times 10^{+35}$ per sec	$(\varphi\sigma)_{Be^7} \times 10^{+35}$ per sec	$(\varphi\sigma)_{B^8} \times 10^{+35}$ per sec	$(\varphi\sigma)_{N^{13}+O^{15}} \times 10^{+35}$ per sec
H^3	$(2.5 \pm 0.3) \times 10^{+2}$	$(2 \pm 1) \times 10^{+2}$	$(1.7 \pm 0.8) \times 10^{+1}$	$(3.8 \pm 2) \times 10^{+1}$
Li^7	0	0	$(1.1 \pm 0.6) \times 10^{+1}$	(3 ± 1.5)
B^{11}	0	0	(4.7 ± 2.5)	0
Rb^{87}	$(3.8 \pm 0.4) \times 10^{+1}$	$(3 \pm 1.5) \times 10^{+1}$	(2.4 ± 1.3)	(6 ± 3)

References

1) R. Davis, Jr., Phys. Rev. Letters 12 (1964) 302. R. Davis, Jr. and D. S. Harmer (private communication).

2) W. A. Fowler, Astrophys. J. 127 (1958) 551; P. D. Parker, J. N. Bahcall, and W. A. Fowler, Astrophys. J. 139 (1964) 602.

3) J. N. Bahcall, Science (to be published, 1964).

4) The use of Sr^{87} as a possible detector of low-energy neutrinos was originally proposed by A. W. Sunyar and M. Goldhaber, Phys. Rev. 120 (1960) 871.

5) The suitability of B^{11} as a target for detecting B^8-neutrinos was suggested to the author by F. Reines (private communications, 1964). Reines also suggested that the reaction $B^{11}(\nu_e,e^-)C^{11}$ could be used to establish the direction of the neutrino source by observing the direction of the created electron.

6) The idea of using the direction of the created electrons to establish the direction of the neutrino source was originally proposed by G. Marx and N. Menyhard, Science, 131 (1960) 299.

7) J. N. Bahcall, Phys. Rev. Letters 12 (1964) 300; Phys. Rev. 135 (1964) B137. The parameters needed in the present study can all be calculated from known experimental data except for the $\langle\sigma\rangle^2$ for excited-state transitions in the reaction $B^{11}(\nu,e^-)C^{11*}$; these matrix elements can, however, be estimated with sufficient accuracy from a sum rule for Gamow-Teller matrix elements (J. N. Bahcall and H. A. Weidenmüller, to be published).

8) The asymmetry parameter α given in table 1 was calculated by averaging over all relevant states weighted according to their relative population by solar-neutrino absorption. If one only counts electrons with energies in excess of some minimum energy W_{min}, α (for Li^7 and B^{11}) is a function

of W_{min}. The asymptotic value of α for Li^7 (B^{11}) is + 0.1 (+ 0.5) for $W_{min} \gtrsim 13.6$ MeV ($\gtrsim 12$ MeV).

9) E. J. Konopinski, Ann. Rev. Nucl. Sci. 9 (1958) 99.

10) R. L. Sears, Astrophys. J. 140 (1964) 477; J. N. Bahcall, W. A. Fowler, I. Iben, Jr., R. L. Sears, Astrophys. J. 137 (1963) 344.

11) F. Reines and R. M. Woods, Jr. (to be published).

12) A possible method for distinguishing between tritium-decay electrons and neutrino-produced electrons might be to cover the tritium target with a thin absorber sufficient to stop the decay electrons without preventing the neutrino-induced electrons from reaching a surrounding scintillator.